# Postflight Performance of GPS/INS Navigation for a Hypersonic Reentry Body

19961218 001

Thomas M. Hattox
James J. Kinnally
Steven J. Mochtak
William J. Farrell

*The Johns Hopkins University Applied Physics Laboratory*
*Johns Hopkins Road*
*Laurel, Maryland, 20723*

## Abstract

This paper dicusses the postflight evaluation of navigation performance in a hypersonic reentry body using GPS and inertial instrumentation. The evaluation was performed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) using independnt GPS and INS data recorded from a Navy reentry body on a recent flight test. The reentry body was configured with a dual frequency wideband GPS translator developed by JHU/APL, along with a complementary ground station used for receiving and recording the translator data. The GPS data are used postflight to update the INS trajectory, as well as to evaluate the INS performance. The results provide a prediction of real-time performance which could be expected from an integrated GPS/INS navigator in a highly dynamic environment. Error budgets are shown in the impact domain for multiple scenarios, including (1) INS only, (2) INS with early reentry phase GPS, and (3) INS with early and post-plasma reentry GPS. Any use of GPS data during reentry phase significantly improves the trajectory and impact performance of the INS. Post-plasma GPS, although a challenge to acquire and track, provides a dramatic improvement in predicting impact position and time-of-impact.

## Introduction

Precision navigation of hypersonic reentry bodies on ballistic trajectories has been a difficult challenge for inertial navigation systems (INS). The very high g-loads during reentry excite significant error mechanisms in the inertial instruments.



Fortunately, the high g-forces are present for only a relatively short time prior to impact, so the resulting trajectory errors do not have time to grow unbounded. Particularly difficult is the requirement that the reentry body INS, which can be aligned with the missile INS during boost flight, accurately maintain its orientation after separation, during the long freefall portion of the trajectory prior to reentry. This is necessary because of the very large sensitivity of reentry trajectory errors to initial orientation of the accelerometers at the onset of reentry forces.

Reentry navigation capability can be greatly improved by the integration of GPS, along with an INS, into the reentry body. GPS translators and receivers are now available which meet the required size, weight, and power constraints for this application. The onboard GPS system can be used in conjunction with the INS to provide a precision evaluation of the ballistic (without control) reentry performance. GPS can also be used to evaluate the INS performance in the reentry environment. The GPS/INS package, when integrated with a vehicle control system, could provide the navigation capability for future maneuvering reentry bodies. The GPS/INS only configuration can provide performance predictions for such a controlled reentry vehicle.

A special reentry body, configured with an INS and a GPS translator, was flown on a Trident II test flight in December 1995, as part of the Extended Navy Test Bed (ENTB) program. This test provided the instrumentation necessary for a precision evaluation of the performance of the INS in a reentry environment, as well as the opportunity to assess the potential inflight accuracy performance of a reentry vehicle with an integrated navigation/control system. This paper discusses the results of these evaluations.

# AD NUMBER

AD-B217 369

# NEW LIMITATION CHANGE

TO

**DISTRIBUTION STATEMENT A -**
**Approved for public release; Distribution unlimited.**

Limitation Code: 1

FROM

DISTRIBUTION STATEMENT - B

Limitation Code: 3

# AUTHORITY

P.M. Wallace, Via DON Dir SSP Ltr., dtd Sep 23, 1996

JHU/APL has been involved with GPS instrumentation systems for many years. In support of the Navy's Trident programs, JHU/APL has been applying post-flight GPS metric tracking techniques since 1978.[1,2] The techniques, developed at JHU/APL, are used to provide precision trajectory measurements for post-flight guidance evaluation of Trident missile test flights. A GPS translator on the test missile receives GPS signals and converts the signals to S-band for re-transmission to the ground telemetry station. The telemetry station receives the translated GPS signals, amplifies, down-converts, digitally samples, and then records the data for post-flight playback. A special facility, at JHU/APL, is used to track the GPS signals during post-flight playback of the recorded data. The system, known as SATRACK, was operational for the Trident I system in 1978 with a major upgrade for the Trident II system in 1987.[3] The current capability, designed by JHU/APL to support the ENTB program, provides post-flight receiver operations for the full GPS signal (i.e. P(Y) code modulation at both the L1 and L2 frequencies).

## Test Configuration

A conceptual diagram of the reentry body test flight, focusing on the GPS and INS instrumentation, is shown in Figure 1. The INS is a strapdown inertial navigation system known as the Reentry Inertial Measurement Unit (RIMU). The GPS instrumentation system consists of an onboard translator and antenna system, ground based receiving and recording equipment, and post-test processing hardware and software designed and developed at JHU/APL. The reentry body was equipped with a wideband translator developed at JHU/APL to support this program. This unit, which is much smaller than older models, receives (at L-band) and re-transmits (at S-band) the full GPS signal spectrum, containing the complete signal information for all satellites in view of the reentry body.

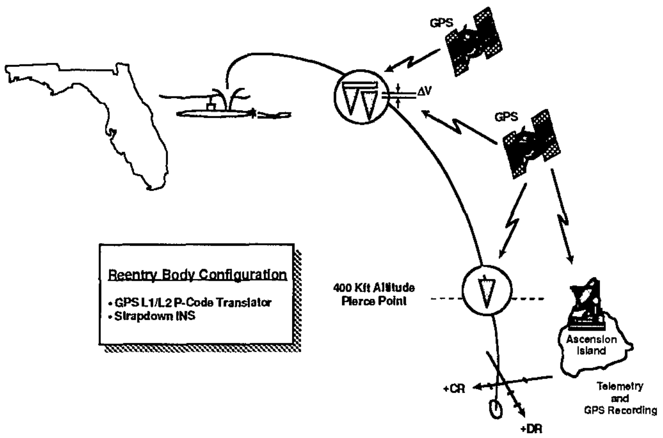



**Figure 1.** Flight Test Configuration

The translator output is captured by a JHU/APL developed portable receiver/recorder system called the Portable Ground Equipment (PGE), housed in an instrumentation suitcase weighing just 42 pounds. The PGE down-converts and digitizes the S-band signals and records these digital samples on an internal recording subsystem. The PGE is returned to JHU/APL after the mission where the recorded GPS data are post-flight processed within the SATRACK facility.

The antenna system for a reentry body is necessarily constrained by the requirement that the aerodynamic characteristics of the body not be compromised. The test body was configured with a four element patch antenna located on the base of the vehicle. The S-band downlink was provided by the standard RB telemetry antenna system. Since the body is spin stabilized, this configuration introduces an interferometric effect in both the up-link and the down-link which must be accommodated in the phase tracking loops. Also, the location of the L-band antenna on the base limits visibility in the forward RB direction, as shown in Figure 2.

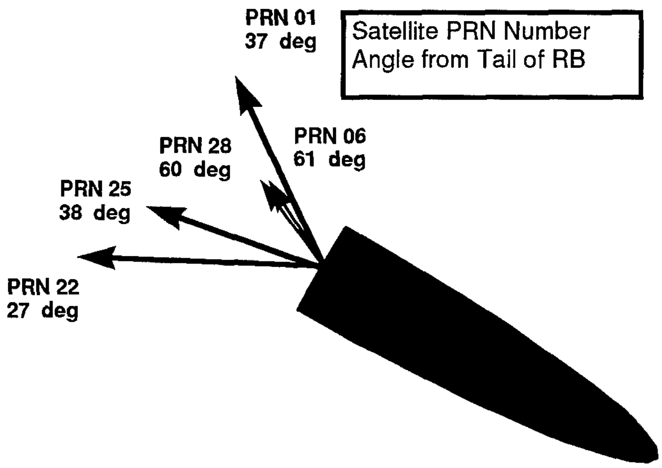



**Figure 2.** GPS Satellite Visibility

Thus the number and geometric configuration of available satellites is somewhat restricted relative to the full satellite complement available to an omnidirectional antenna system at the RB position. For this test, only five satellites were usable on average, providing an average Positional Dilution of Precision (PDOP) factor of 3.1. In addition, during a significant portion of the high-g reentry phase, the GPS signals were lost due to the plasma "blackout" effect on RF signals.

The use of a translator with post-test processing minimizes the GPS losses suffered by a reentry body. A translator has several important advantages over a receiver: (1) it is simpler than a receiver and therefore more reliable, (2) it can handle the signals from any number of satellites, (3) it can utilize post-test precision ephemerides and data corrections in post-processing, and (4) it can acquire range and doppler data within a few seconds of GPS signal availability, when operating with suitable ground post-processing equipment. For this test, GPS signals were tracked post-flight during the final few seconds after emergence from plasma and before impact.

## Post-Processing Methodology

An overview of the system elements for post-flight processing is shown in Figure 3. Use of tracking aids generated from the known satellite ephemerides and RIMU telemetry allow narrowband tracking of the vehicle even during the high dynamics of reentry. Deterministic compensations are applied to the raw tracked pseudo-range and doppler data through an extensive data correction/editing process. Tracking corrections include: (1) satellite clock errors, (2) ionosphere, (3) troposphere, (4) RB and satellite antenna lever arms, (5) RB antenna phase errors and twist effects, and (6) relativity.

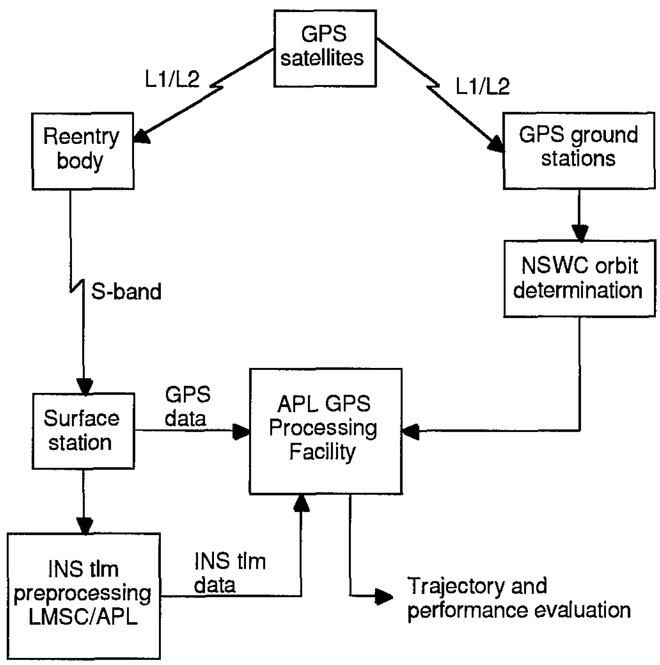



**Figure 3.** System Elements for GPS Processing

The processing system uses precise post-test GPS orbital ephemerides including full satellite covariances. The RB reference trajectory, provided by a combination of RIMU telemetry and freefall integration of gravity, is combined with the range and doppler measurements in a Kalman filter/smoother. The post-processing software uses high fidelity models for both the RIMU and the GPS tracker instrumentation. A factorized (UD) filter/smoother is used to enhance the numerical stability and efficiency of the very large (over 150 states) estimation process.

The GPS range measurements are implemented as instantaneous range updates at specified measurement times. The doppler measurements are implemented as link delta ranges over the measurement intervals. Delay states are used in the filter to manage the information required at both ends of the doppler count, as well as to account for the correlation of the measurements between intervals when continuous doppler counts are available. Both range and doppler measurements are link differenced to eliminate common translator and downlink errors. The filter model for each satellite link consists of a fourteen state error model.

## RIMU Orientation Uncertainty

The primary phases of flight for the postflight processing of RIMU data, in chronological order, are: turn on and initialization, start onboard navigation, predeployment, release (a.k.a. deployment) and spin-up about the longitudinal (roll) axis, coast or "over-the-top", arrival at Pierce Point (a trajectory point with an altitude of 400 kft), Reentry, and surface impact. The vehicle body frame (RB frame) has axes of roll, pitch and yaw.

Orientation uncertainty at Pierce Point (PP) is important because it becomes the initial uncertainty for the Reentry phase. Sizable RIMU orientation uncertainty during the high-g portion of reentry can result in significant navigation uncertainty near the end of flight. The uncertainty about the RB roll axis has the least effect on reentry navigation uncertainty while the sensitivities for pitch and yaw for this trajectory are greater by about a factor of 30. A description of the contributors to PP orientation uncertainty is included in the results for this experiment.

The RIMU computes an onboard orientation solution using compensated gyro output. This solution represents the time history of the orientation of the non-inertial RIMU Platform Frame (P frame) relative to the initial orientation of the P frame (the P frame is the orthogonal gyro input axes frame). At the start of RIMU onboard navigation the inertial navigation frame, the I frame, is defined to be coincident with the P frame (the onboard navigation solution is in the I frame). The onboard orientation solution is therefore the time history of the TIP transformation matrix (this right to left notation indicates a transformation from the P to the I frame). The initial error in TIP, which could be described as an initial orientation error, is *zero* because of the I frame definition. The initial uncertainty in the elements of TIP *is also zero* because it is defined to be the identity matrix. The P frame is fixed relative to the RB frame.

For postflight analysis using measurements external to the RIMU, the measurements must be put in the I frame, or the RIMU trajectory must be put in the inertial frame of the measurements, or the trajectory and measurements must be put in a common inertial frame. In any case, a transformation matrix relating two inertial frames is needed. Such a transformation matrix would also be needed for any real time GPS aided navigation.

In general, the orientation uncertainty results from uncertainty in the transformation matrix that relates the RIMU inertial navigation frame (I) to the inertial navigation frame selected for postflight processing (the "R" frame was selected so the matrix is TRI; the R frame is an Earth-centered inertial frame), as well as uncertainties in the RIMU gyro calibrations. The initial postflight orientation uncertainty of the RIMU is caused by mechanical misalignments. These misalignment uncertainties can be large (~ 2000 arcsec per axis 1 sigma) from an inertial navigation perspective. The orientation uncertainty then increases due to the RIMU gyro error model. By the time of RB release the increase is small. Once the RB/RIMU is spun up, the rate of increase of the uncertainty is larger. The larger rate of increase is due to the roll gyro scale factor being driven by the RB/RIMU angular velocity about the roll axis. During the coast (or "over-the-top") phase of flight the orientation uncertainty propagates according to the gyro error model and the uncertainty continues to increase. The uncertainty about the roll axis increases greatly. Because of coning during the coast phase the uncertainties about the pitch and yaw axes also increase due to the roll gyro scale factor uncertainty. The amount of increase for these two axes is largely a function of RB half cone angle.

The initial orientation uncertainty for the reentry phase (PP orientation uncertainty) thus comes primarily from two sources: the uncertainties in the mechanical misalignments at the start of RIMU onboard navigation, and the accumulation of uncertainty due to the gyro error model. Essentially all of the gyro error model contribution occurs during the coast phase. The roll gyro scale factor uncertainty dominates the coast phase contribution. The uncertainty contribution from the mechanical misalignments can be virtually eliminated by performing a boost phase alignment with the missile Inertial Measurement Unit (IMU). Performing this alignment with a GPS calibrated IMU provides only a small improvement over IMU only, due to the high accuracy of the IMU. Baseline postflight processing uses the GPS calibrated IMU because it is readily available. Results are shown for two cases: with and without predeployment IMU/GPS alignment. Orientation results are presented in the RB0 frame. This is an inertial frame that coincides with the RB axes at the time of release.

**Predeployment Orientation Uncertainty**

The initial (mechanical misalignment) uncertainty without IMU/GPS alignment was greater than or equal to 1000 arcseconds per axis. With alignment, the initial uncertainty was reduced to less than 5 arcseconds per axis. The contribution to uncertainty at deployment from the gyro error model is small (a few arcseconds per axis). Without aligning the RIMU with IMU/GPS, the initial mechanical misalignment uncertainty dominates the predeployment phase, as shown in Figure 4. Predeployment alignment of the RIMU with IMU/GPS greatly reduces the orientation uncertainty at the time of RB release.

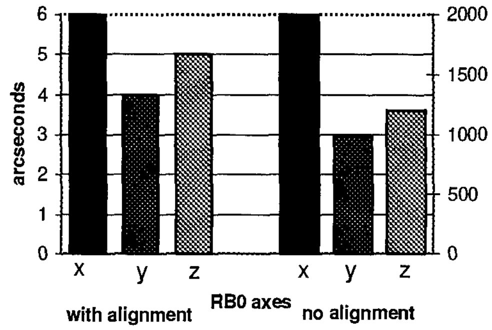



**Figure 4.** Orientation Uncertainty at Deployment (one-Sigma)

**Pierce Point Orientation Uncertainty**

The orientation uncertainty propagates from the time of release to the time of PP in accordance with the gyro error model. The dominate source of orientation uncertainty at PP is due to roll gyro scale factor uncertainty. Even with the small scale factor uncertainty for these gyros (Ring Laser type manufactured by Honeywell), the combination of long coast time and RB spin rate resulted in an additional build up of uncertainty since RB release of approximately 1000 arcseconds about the RB0 x axis, as shown in Figure 5. The roll gyro scale factor uncertainty also contributes to the PP pitch and yaw uncertainties.

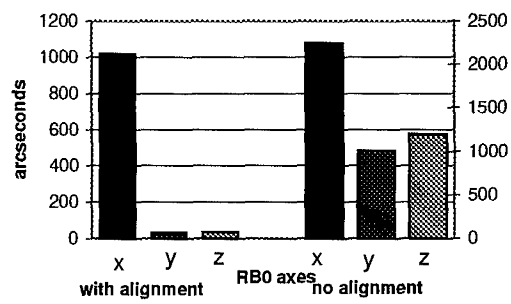



**Figure 5.** Orientation Uncertainty at Pierce Point (one-Sigma

The orientation accuracy goal at PP for the RIMU is 800, 200 and 200 arcseconds 1 sigma about the roll, pitch and yaw axes, respectively, using boost IMU alignment. The RB0 x axis is roughly aligned with the RB roll axis (to within the RB half cone angle) at PP and the RB0 y and z axes are roughly in the same plane as the pitch and yaw axes. With predeployment IMU/GPS alignment, the realized RB0 x axis uncertainty is commensurate with the goal for that axis and the y and z axes uncertainties are well within the goal. The uncertainty about the roll axis has the least effect on reentry navigation uncertainty while the uncertainties about pitch and yaw have the greatest. Without predeployment IMU/GPS alignment, the realized orientation uncertainties clearly far exceed the accuracy goal. Furthermore, the large y and z uncertainties of 1000 and 1200 arcseconds, respectively, would result in very large navigation uncertainties near the end of the flight. For this trajectory, the impact position uncertainty would be on the order of 1000 feet.

## RIMU Orientation Alignment Process

In the baseline postflight processing, the missile IMU is calibrated with GPS before RIMU alignment. This results in a very accurate and precise IMU trajectory. RIMU orientation alignment is a two step process resulting in a corrected TRI matrix whose elements have small uncertainties. Both coast and predeployment phase alignments are done. The corrected TRI matrix is used with the RIMU orientation solution to calculate a corrected time history of RIMU attitude in the desired coordinate frame.

A Coast Kalman Filter (CKF) employing conservation of angular momentum is used first. This process is shown in Figure 6. RIMU telemetry and RB mass properties are input to the filter. The angular momentum of the RB/RIMU is computed in the filter using RIMU gyro output and RB mass properties. The error model includes the misalignment angles between RB frame and the RIMU P frame. Estimates and uncertainties of these angles are used to improve the TRI matrix. Due to the direction of the angular momentum vector, the misalignment about the roll axis is almost non-observable. Estimates of these angles are desirable in and of themselves for purposes of transforming RIMU instrument output into the RB frame.

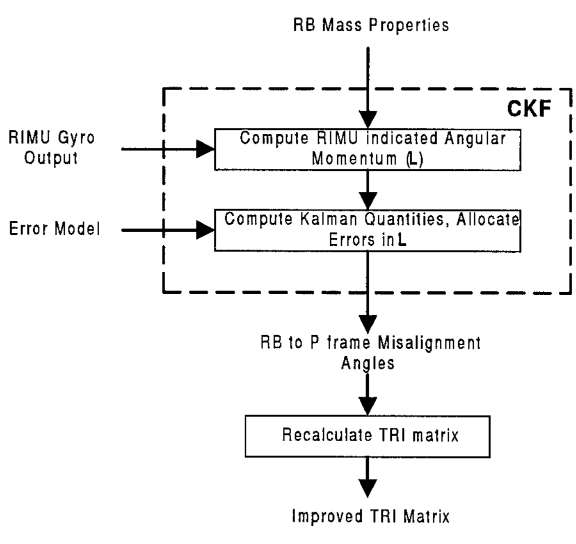



**Figure 6.** RIMU Coast Alignment Process

Next, a (predeployment) Boost Kalman Filter (BKF) based on double integral of specific force matching between the RIMU and the missile IMU is used as shown in Figure 7. The filter measurements are based on the difference between the RIMU indicated trajectory and the precise missile IMU trajectory. The mechanical misalignments still present in the TRI matrix cause the RIMU indicated trajectory to diverge from the accurate IMU trajectory. The filter error allocation results in estimates and uncertainties for these misalignments. The TRI matrix is then further corrected and a more precise and accurate time history of RIMU orientation is computed.

The alignment process could be performed in one step but it is desirable to separate out the RB to RIMU (P frame) misalignment angles.

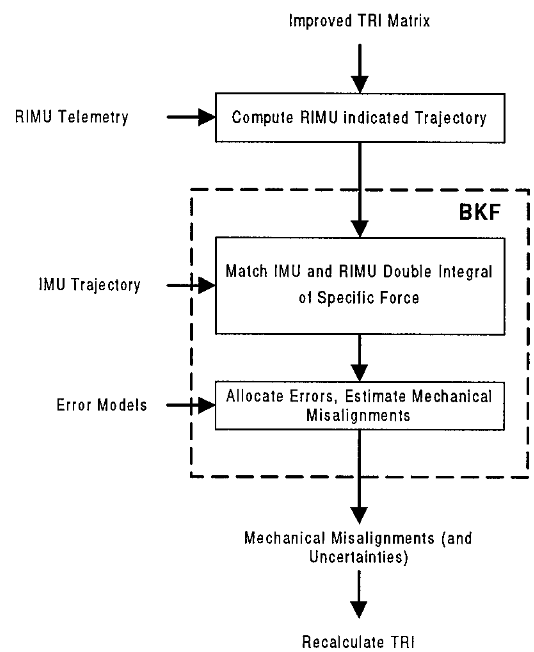



**Figure 7.** RIMU Boost Alignment Process

## Reentry Methodology

Reentry is defined to cover the region starting at 400,000 feet (pierce point) down through the atmosphere to surface impact. Reentry trajectory solutions have been generated post-flight in the past by navigating the reentry body (RB) using the RB/INS accelerometer and gyro output data. The objective of this analysis is to determine the enhanced navigation performance attainable post-flight by incorporating independent GPS measurement data into the reentry trajectory solution.

A kalman filter is used post-flight to integrate the GPS measurement data into the reentry trajectory solution as shown in Figure 8. The reference trajectory for the kalman filter is generated by navigating the RB through reentry using the RB/INS accelerometer and gyro output data. The RB/INS reentry trajectory is initialized at pierce point with its state vector and covariance derived from a boost/deployment analysis with the IMU / INS, which is then propagated over to pierce point.

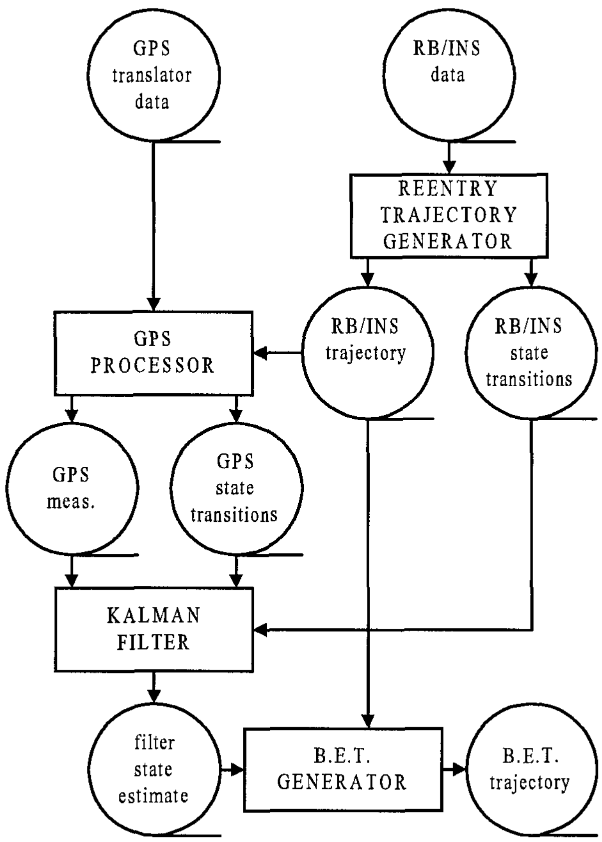



**Figure 8.** GPS / INS BET Processing Flow

The independent GPS measurement data in the kalman filter consists of range and doppler data. Emphasis is placed on the fact that the GPS data acquired during the flight and used in the analysis is derived from tracking of the P-code signal. The P-code signal versus the CA-code signal results in a significant decrease in the noise level of the range data. This represents the first case of an RB, flown with a translator, able to utilize the P-code signal during a flight.

The patch antennas which received the GPS signal were located on the base of the RB. This restricted the satellites in view of the RB to those positioned behind the RB. This non-optimal satellite geometry resulted in a moderate degradation in the GPS performance relative to full coverage.

The kalman filter is used to solve for three separate reentry trajectory solutions: (1) RB/INS only, (2) RB/INS + pre-plasma GPS measurements, and (3) RB/INS + pre- and post-plasma GPS measurements. Pre-plasma GPS measurements are those recorded before the plasma sheath forms around the RB during reentry, causing the attenuation and eventual loss of the GPS signal at 112,000 feet. Post-plasma GPS measurements are those recorded by the RB after the blackout period ends (8700 feet), but before surface impact.

The three trajectory cases are discussed in greater detail in the following sections.

## <u>Orientation Estimation During Reentry</u>

The body reentered the atmosphere at nearly zero angle of attack. It was spinning at an angular rate of approximately 700 degrees per second about its longitudinal (roll) axis. It was also coning at a much lower rate. Body orientation is not directly observable with the GPS antenna configuration used on this body. It would be possible with a minimum of three antennae properly configured to directly measure orientation. However INS orientation error can be inferred in a high specific force environment from GPS range and doppler measurements.

The inertial navigation system (INS) maintains orientation by integration of the onboard gyro data both during vacuum flight and reentry. In our initial case no GPS measurements were used during reentry. Figure 9 shows the one sigma uncertainty for the total orientation magnitude from pierce point to impact. As expected, the uncertainty in body orientation grows when no external measurements are used.

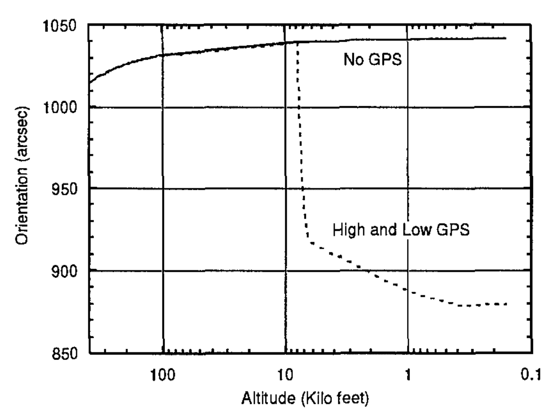



**Figure 9.** INS Total Orientation Uncertainty for GPS Filter

### Reentry Orientation with High Altitude GPS Only

Position and velocity are directly observable with GPS measurements. During vacuum flight, errors in INS orientation do not cause errors in position and velocity. Thus in vacuum flight, body orientation is not observable from GPS measurements. However very large forces, especially along the roll axis, are present in reentry with very large effect on velocity and position. This makes orientation very observable about the pitch and yaw axes. However, orientation about the roll axis is less observable than pitch and yaw.

A filter run was made using high altitude (pre-plasma) GPS measurements. The GPS measurements went down to about 112,000 feet in altitude. INS orientation was not observable. The orientation uncertainties were virtually the same as for the no GPS case. At these altitudes (greater than 112,000 feet), the aerodynamic forces on the body are still not very large. The time in which appreciable force has acted is also small. Thus, the effect on velocity and position due to the error in measured drag, caused by an error in INS orientation, is too small to be estimated.

**Reentry Orientation with High and Low Altitude GPS**

Figure 9 also shows the same plot of orientation uncertainty but with low altitude (post-plasma) GPS measurements . The plot shows the magnitude of the uncertainty including roll. It indicates that orientation is observable. What is not shown is that the observability is greatest in pitch and yaw. The reduction in the roll uncertainty is 15%, pitch is 50% and yaw is 67%. The roll is somewhat observable due to its correlation to pitch and yaw. However, the low observability in roll also means that roll estimation is not very important for position estimation. In fact, for the test flight, the effect of a pitch or yaw orientation error at pierce point was about 30 times greater than for an equivalent roll orientation error.

**Smoothed Reentry Uncertainties**

Figure 10 shows the smoothed uncertainties for the high only and the high and low GPS measurement cases. The smoothed uncertainty at any given point includes all the measurements, both before and after the given point, used in the filter run. The filtered uncertainties include only the data up to the time of the given point. These represent what may be possible in a 'real time' system. The smoothed uncertainties represent the best results that can be obtained from post flight processing. Figure 10 shows that there is a substantial increase in knowledge of orientation obtained from the relatively small number of low altitude GPS post-plasma measurements.

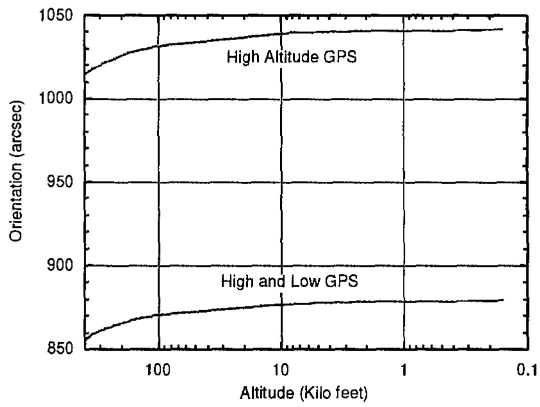



**Figure 10.** INS Total Orientation Uncertainty for Post Processed GPS Smoother

## Position Estimation During Reentry

**RB/INS Only**

First an open loop navigation of the RB / INS, using no GPS measurements, was completed. This reentry trajectory serves as the reference trajectory in the kalman filter for the cases where GPS measurements are processed.

The initial pierce point (reentry) state vector of the RB/INS reflects the following post-flight updates. First, the RB/INS orientation is updated during the boost/pre-deployment section of the flight through an alignment with the missile IMU. Second, the RB/INS position and velocity are updated post deployment with an estimate of deployment error derived using the RB/INS. Third, the RB/INS instrument errors are calibrated during the boost/pre-deployment section of the flight through a comparison with the missile IMU.

The position uncertainty for the RB/INS only case is 86 feet at pierce point and increases to 93 feet near surface impact. The position uncertainty is the RSS of the three components of position uncertainty. The position uncertainty increases during reentry due to the propagation of the RB/INS error model with time. The initial position uncertainty magnitude of 86 feet at pierce point is primarily due to the uncertainty in the INS measurement of deployment delta velocity. Using only RB/INS outputs for navigation, the surface impact position uncertainty magnitude is approximately 93 feet.

**RB/INS + Pre-Plasma GPS**

In this case GPS measurements in the high altitude region (pierce point to approximately 112,000 feet) are processed in the kalman filter and used to update the RB/INS only reference trajectory. GPS range and doppler measurements are available from 5 satellites. GPS measurements were input into the filter at a one hz rate initially, and increased to 10hz for several seconds when the RB first started to experience the effects of atmospheric drag around 160,000 feet. Plasma sheathing caused the loss of GPS signal at approximately 112,000 feet.

Large prior values were used for the initial RB/INS position and velocity uncertainties. The GPS measurements dramatically reduced these uncertainties very quickly. The position uncertainty (RSS) versus time, starting shortly after pierce point and ending near surface impact, is shown in Figure 11. The data plotted in Figure 11 are from the filtered solution in the kalman filter. The filtered solution includes only the data up to the time of the given point. Thus, these represent what may be possible in a "real time" system. Only a few GPS measurements are needed to drive the RSS position uncertainty down to approximately 6 feet to 7 feet. The position uncertainty eventually approachs 5 feet as further GPS measurements are processed in the kalman filter up until the plasma induced loss of GPS signal at approximately 112,000 feet. The RSS position uncertainty then increases to approximately 24 feet at surface impact, again, due to propagation of the RB/INS error model with time. However, this is still greatly reduced from the surface impact value of 93 feet from the RB/INS only case.

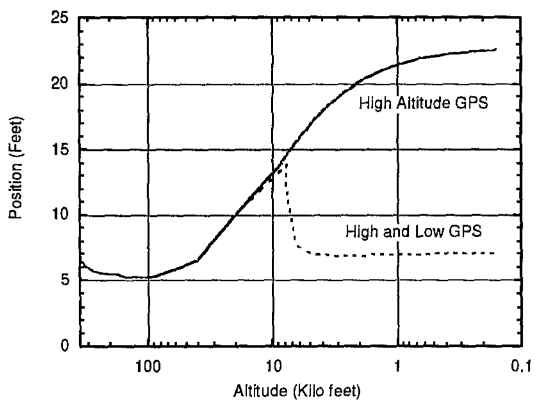



**Figure 11.** INS Total Position Uncertainty for GPS Filter

### RB/INS + Pre- and Post-Plasma GPS

This case includes the GPS measurements recorded after the RB came out of the plasma induced blackout and re-acquired the GPS P-code signal. The GPS data rate in the low altitude region (approximately 8,700 feet to 100 feet above surface impact) was 10 hz. Approximately 2 seconds of range only GPS measurements were recovered. These data were extremely important because they occurred very close to surface impact and were in a very high drag region of the flight. Any RB/INS orientation errors present during the high drag region are highly observable with GPS measurements.

The RSS position uncertainty versus time, starting shortly after pierce point and ending near surface impact, is also shown in Figure 11 along with the RB/INS + pre-plasma GPS measurement case. The high altitude region is the same since the identical kalman filter setup was used. However, after the GPS data gap ends at approximately 8,700 feet, the low altitude GPS range measurements processed in the kalman filter are apparent. The surface impact position uncertainty has a final value of approximately 7 feet versus approximately 24 feet in the RB/INS + pre-plasma GPS measurement case.

### Impact Comparisons To SMILS

Figure 12 is a comparison of all three cases in the impact domain. It is apparent that the post-flight performance capability of a RB/INS instrument can be greatly improved with only a few high altitude GPS measurements, decreasing from a surface impact position uncertainty RSS of almost 93 feet to just under 24 feet. Also, the ability to re-acquire the GPS signal post-plasma further reduces the surface impact position uncertainty to 7 feet.

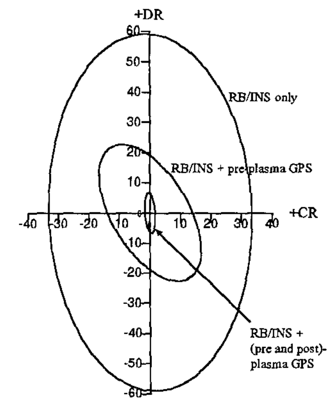



**Figure 12.** Impact Domain Uncertainty for GPS Configuration

The three post-flight reentry trajectory impact solutions are also compared in the impact domain. The surface impact location and time-of-flight of the RB during the actual flight was recorded by a Sonobuoy Missile Impact Location System (SMILS) which has an uncertainty of approximately 20 feet in position and 3 milliseconds in time. Table 1 shows the position and time delta's for each reentry trajectory solution with respect to the SMILS values. The position delta's are in a standard Downrange (DR), Crossrange (CR) frame. The significant improvement at impact provided by the GPS measurements is evident from the Table. The RB/INS only case includes pre-deployment calibration with the missile IMU, which results in an acceptable orientation error at piercepoint Without the calibration, the RB/INS impact performance would be much worse.

| | DR (ft) ($1\sigma$) | CR (ft) ($1\sigma$) | TOF (sec) ($1\sigma$) |
|---|---|---|---|
| RB / INS only | -138 (59) | -7 (33) | -0.0430 (.024) |
| RB / INS + pre-plasma GPS | -21 (23) | +3 (17) | +0.0025 (.004) |
| RB / INS + pre-and post-plasma GPS | +7 (7) | -10 (2) | +0.0056 (.002) |

**Table 1** Impact Domain Comparison To SMILS

## Summary

A postflight evaluation was performed of the navigation performance in a special reentry body configured with an INS and a GPS wideband translator. The GPS data were used to update the INS trajectory and to evaluate the INS performance. The use of pre-plasma GPS data during reentry phase significantly improved the trajectory and impact performance of the INS. The kalman filter results for this case (24 feet one sigma uncertainty at impact) provides a prediction of real-time performance which could be expected from an integrated GPS/INS reentry navigator. Post-plasma GPS, although recovered for only a few seconds prior to impact, provided a dramatic improvement in predicting impact position (7 feet rss one sigma) and time-of-impact.

## REFERENCES

[1] Thompson, T., "Performance of the SATRACK/Global Positioning System Trident Missile Tracking System," IEEE Position Location and Navigation Symposium (1980).

[2] Vetter, J. R., Schwenk, V. L., and Hattox, T. M., "Ballistic Missile Trajectory Reconstruction and Error Estimation from a Satellite-Based Tracking System (SATRACK) of Operational Trident I Flight Tests," *Eighth Biennial Guidance Test Symposium* (1983).

[3] Vetter, J. R., Schwenk, V. L., and Hattox, T. M., "An Improved GPS Based Tracking System for High Accuracy Trident Missile Navigation and Guidance Evaluation," *Fourteenth Biennial Guidance Test Symposium* (1989).

# Postflight Performance of GPS/INS Navigation for a Hypersonic Reentry Body


Thomas M. Hattox
James J. Kinnally
Steven J. Mochtak
William J. Farrell

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723

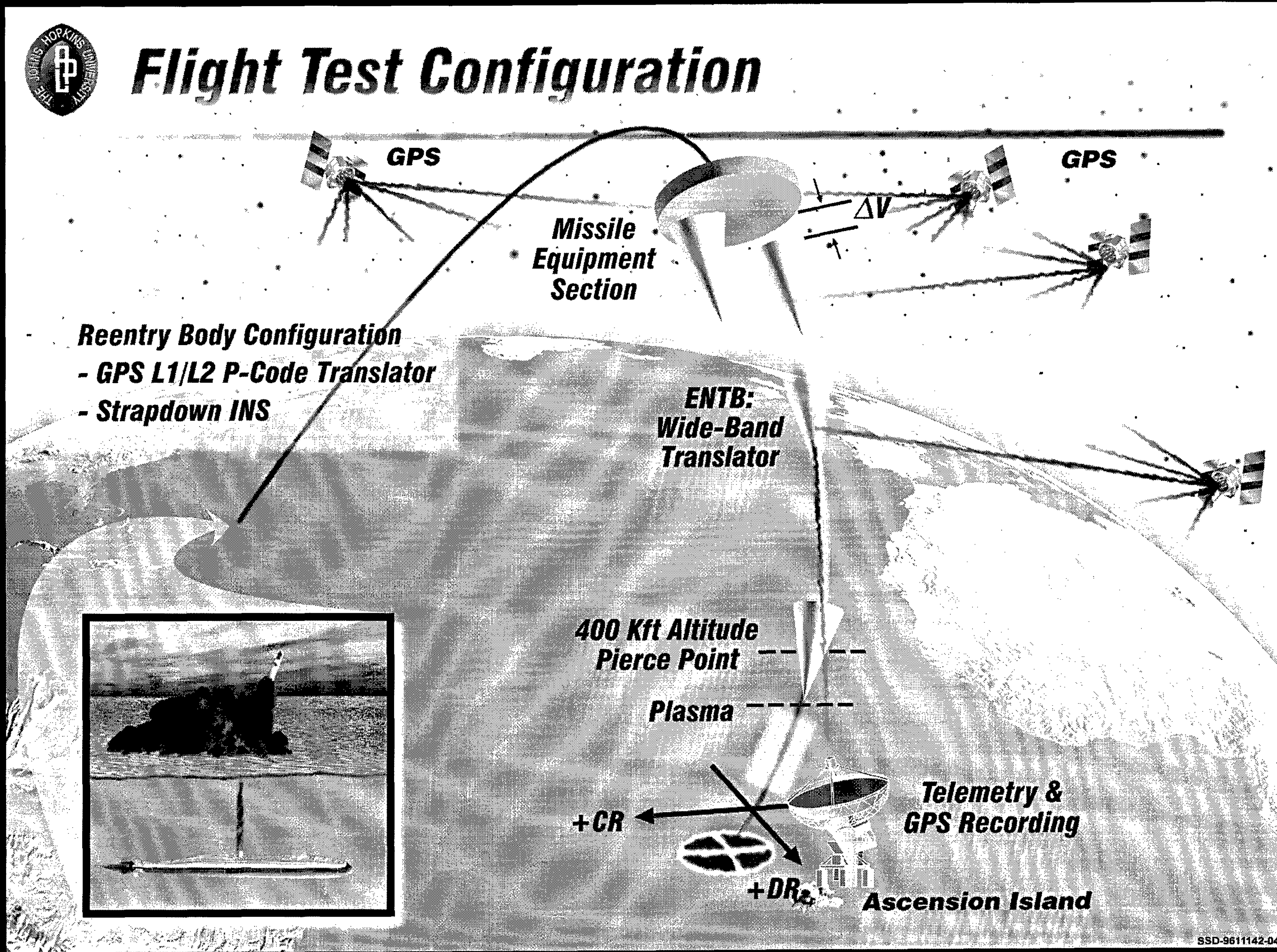

5 December, 1996

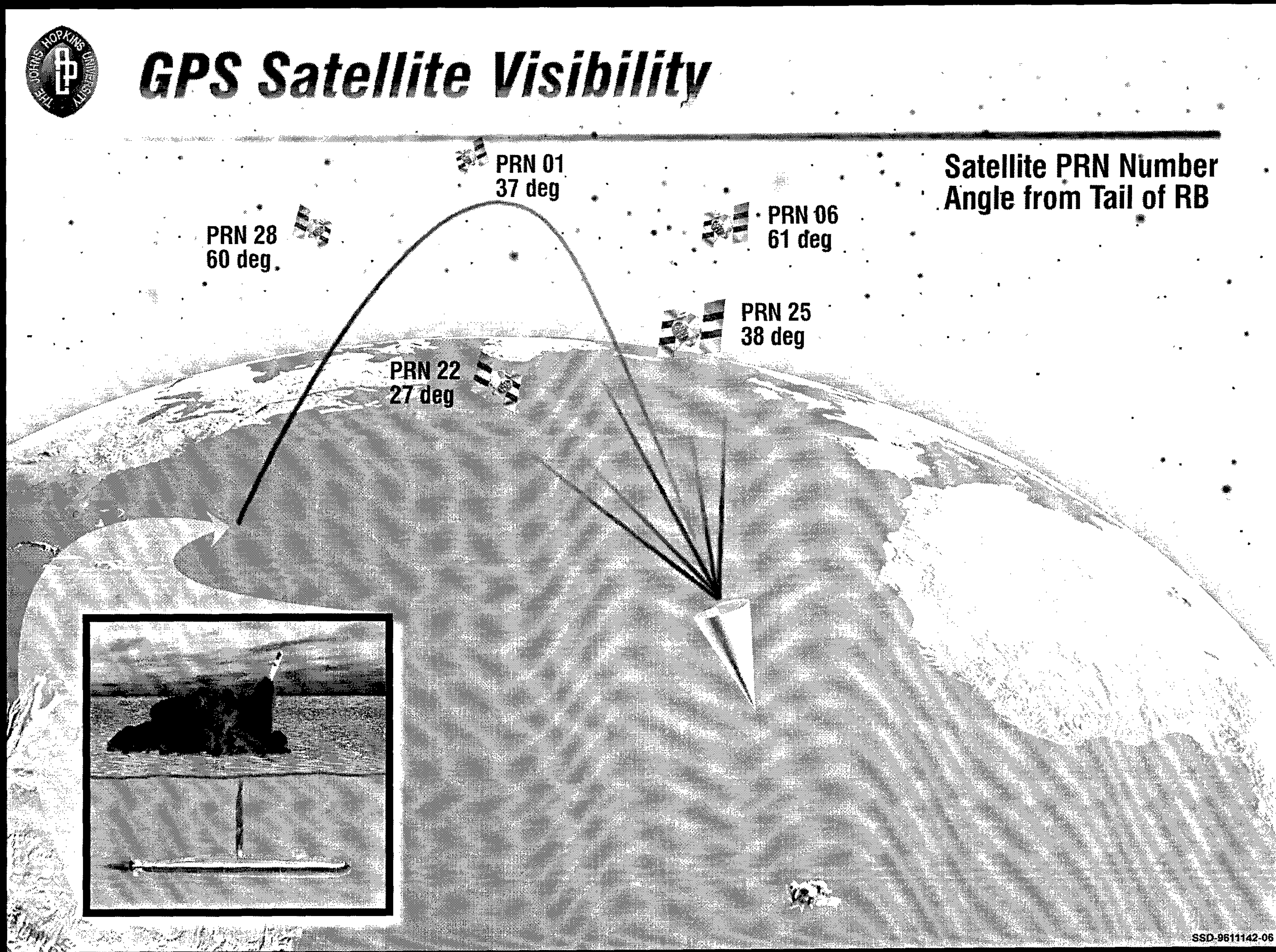


SSD-9611142-01

# Overview

- Motivation
- Flight Test Configuration
- Methodology
- Test Results
- Summary

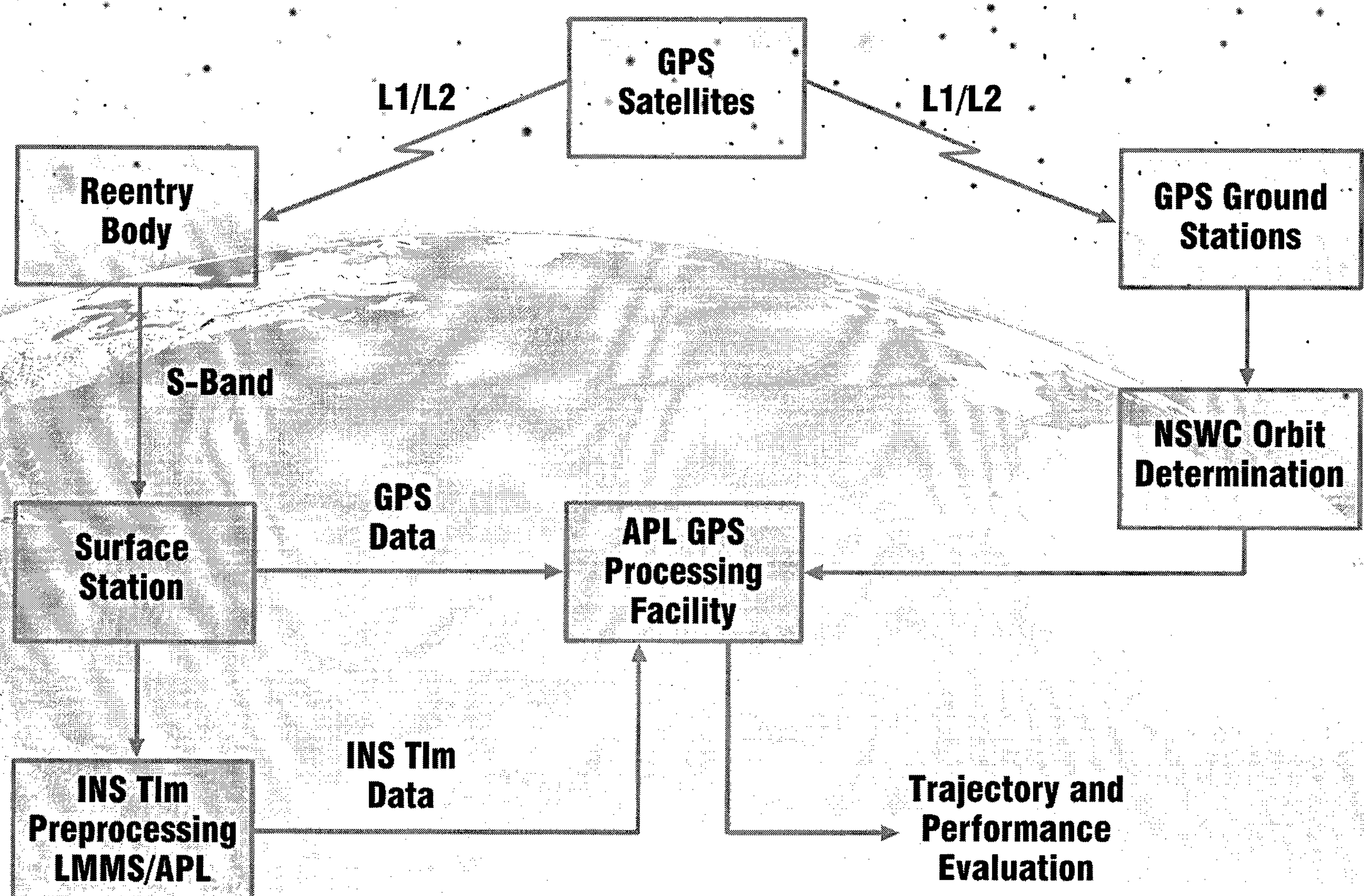

THE JOHNS HOPKINS UNIVERSITY
Flight Test Configuration
GPS
GPS
ΔV
Missile
Equipment
Section
Reentry Body Configuration
- GPS L1/L2 P-Code Translator
- Strapdown INS
ENTB:
Wide-Band
Translator
400 Kft Altitude
Pierce Point
Plasma
+CR
+DR
Telemetry &
GPS Recording
Ascension Island
SSD-9611142-04


THE JOHNS HOPKINS UNIVERSITY
GPS Satellite Visibility
Satellite PRN Number
Angle from Tail of RB
PRN 01
37 deg
PRN 28
60 deg.
PRN 06
61 deg
PRN 25
38 deg
PRN 22
27 deg
SSD-9611142-06

# Translator Advantages for Postflight Evaluation

- Uses All Satellites In View
- Uses Post-Test Corrections For Aiding
- Allows Very Rapid Data Acquisition
- Minimizes GPS Losses In Reentry Environment
    - Antenna Interferometry
    - Plasma Blackout
- Provides Capability To Evaluate Multiple Scenarios Post-Flight
    - Combinations Of Satellites
    - Data Spans
    - Navigation Algorithms
- Robust For Post-Test Evaluation
    - Does Not Depend Upon Or Require Real-Time Tracking

# System Elements for GPS Processing

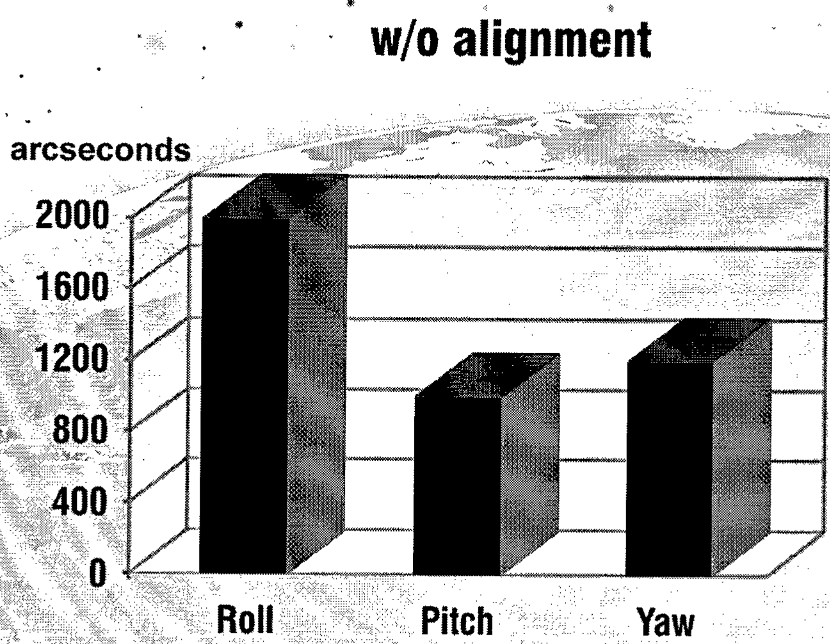


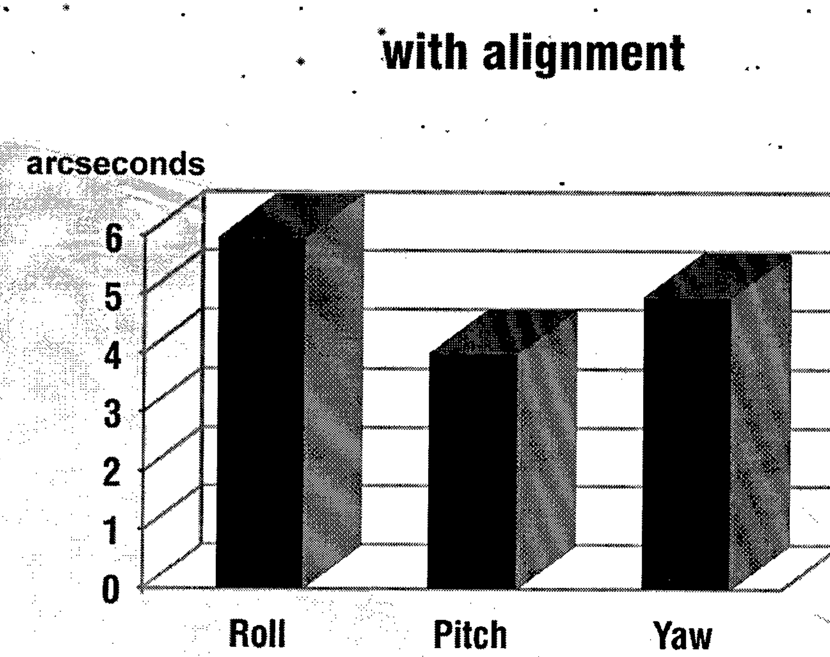

SSD-9611142-08

# INS Pre-Reentry Orientation

- INS Boost Phase Alignment With Missile IMU Provides Low Orientation Uncertainty (5 Arcsec) At Deployment
- Orientation Uncertainty At Pierce Point Is Significant Contributor To Impact Uncertainty
  - Increase Due To Gyro Scale Factor Over-The-Top
    - Spin Stabilized Reentry Body
    - Much Larger About Roll Axis
  - High G-Forces During Reentry Cause Significant Sensitivity To Orientation

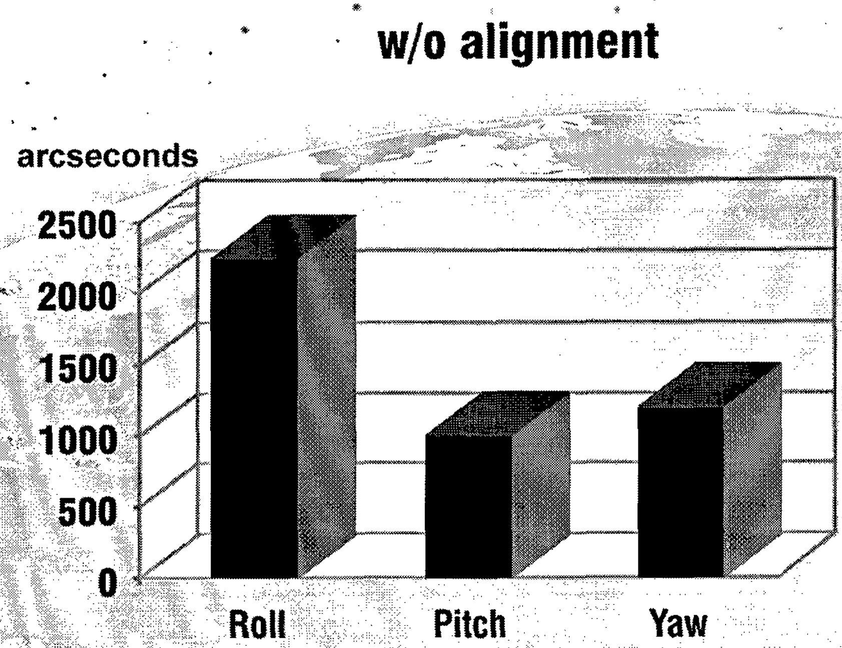
# Orientation Uncertainty at Deployment
## (one-sigma, RBO frame)

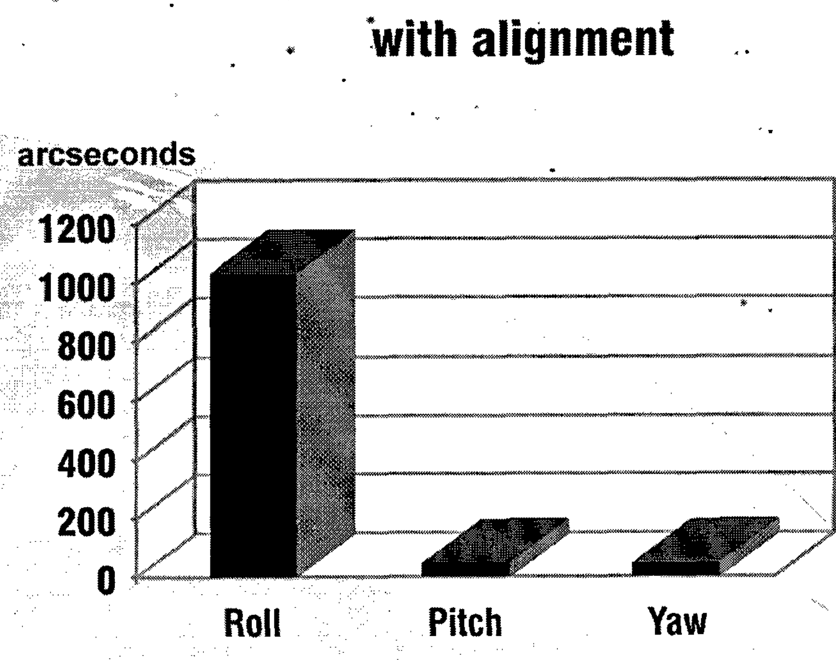



SSD-9611142-11

# Orientation Uncertainty at Pierce Point
## (one-sigma, RBO frame)



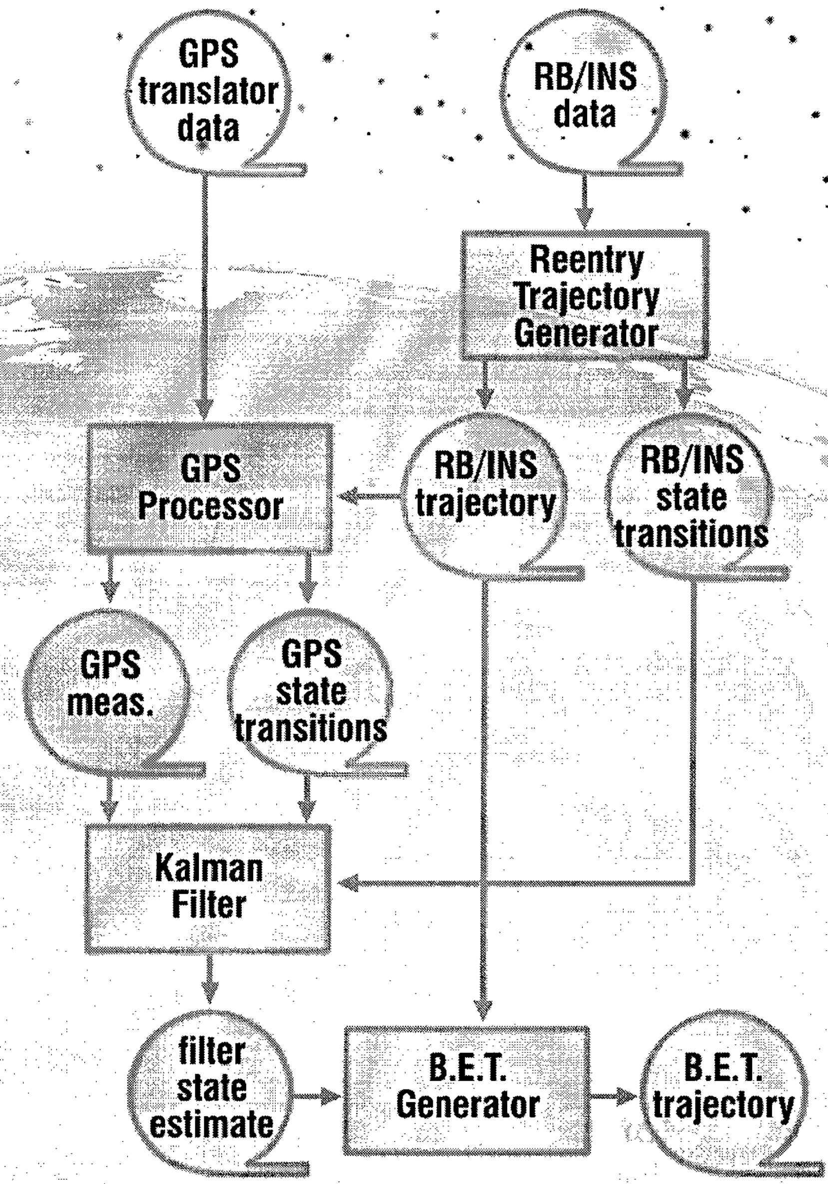




SSD-9611142-12

# Reentry Trajectory Evaluation

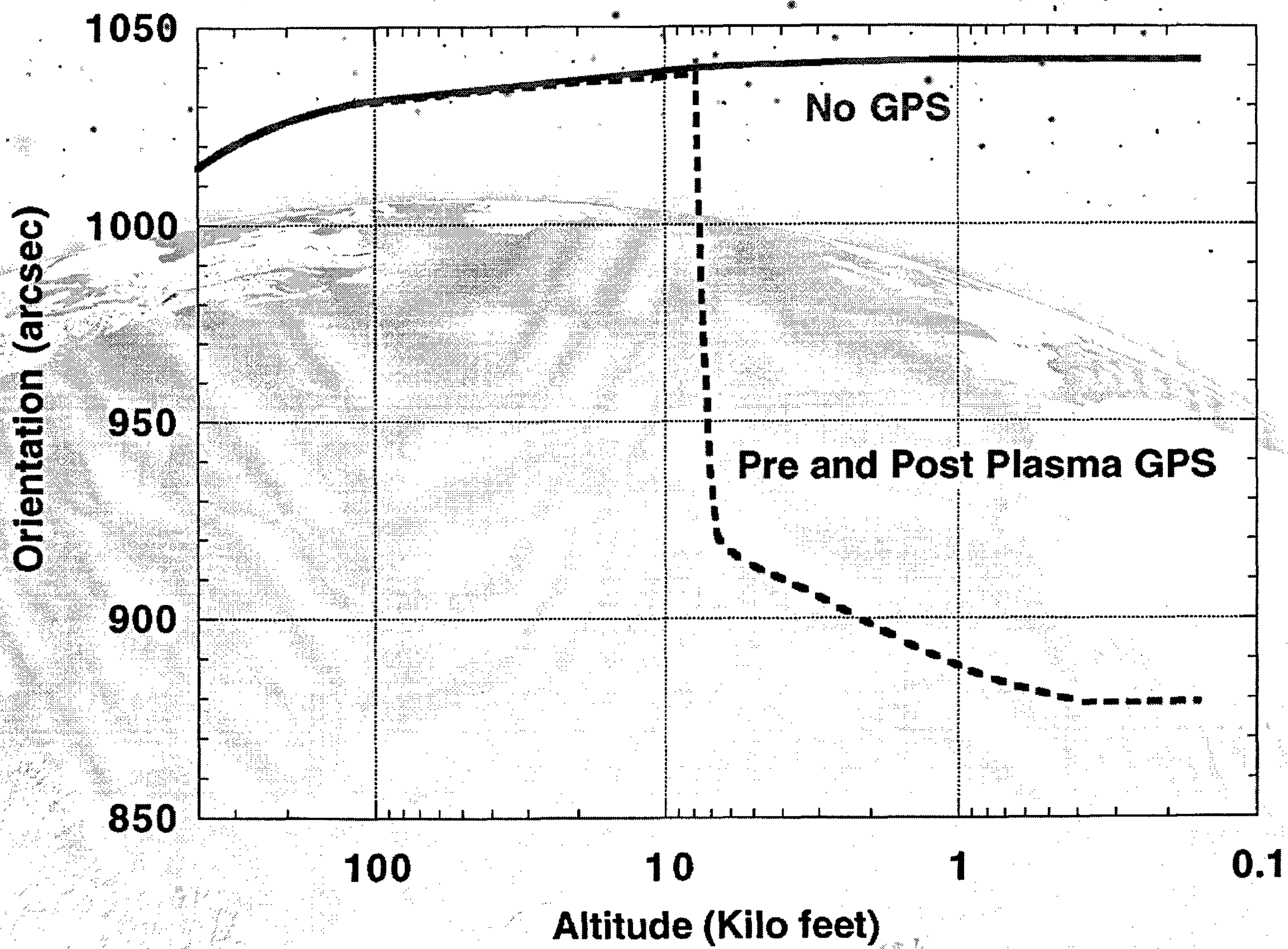
- Three Cases Evaluated
  - INS Only
  - INS + Pre Plasma GPS
  - INS + Pre And Post Plasma GPS
- Comparisons Performed
  - INS Orientation
  - Trajectory Position
  - Impact Position And Time

# GPS/INS BET Processing Flow



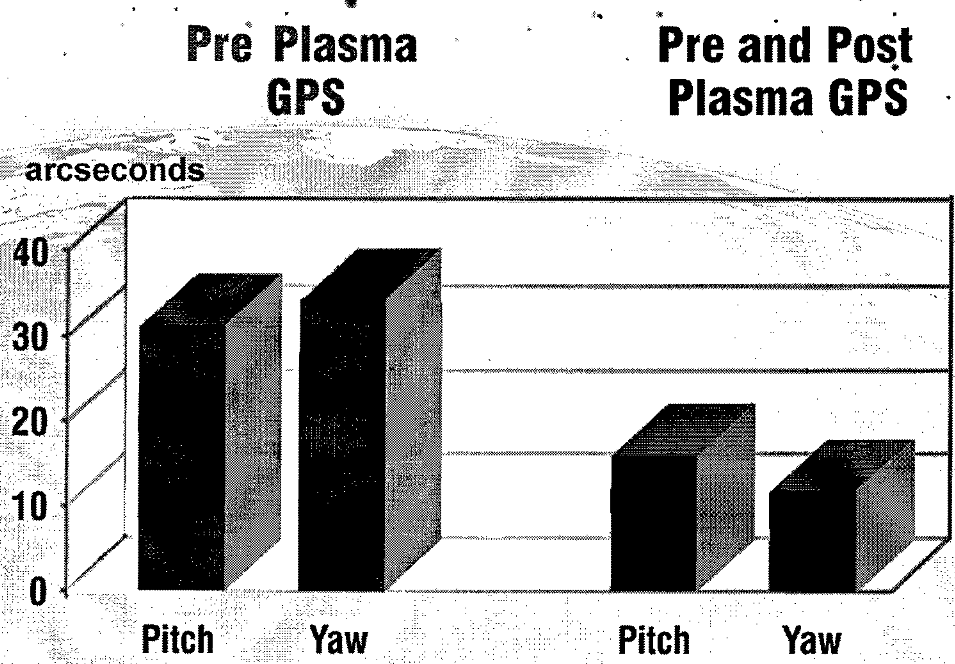

SSD-9611142-14

# INS Orientation Uncertainty for GPS Filter



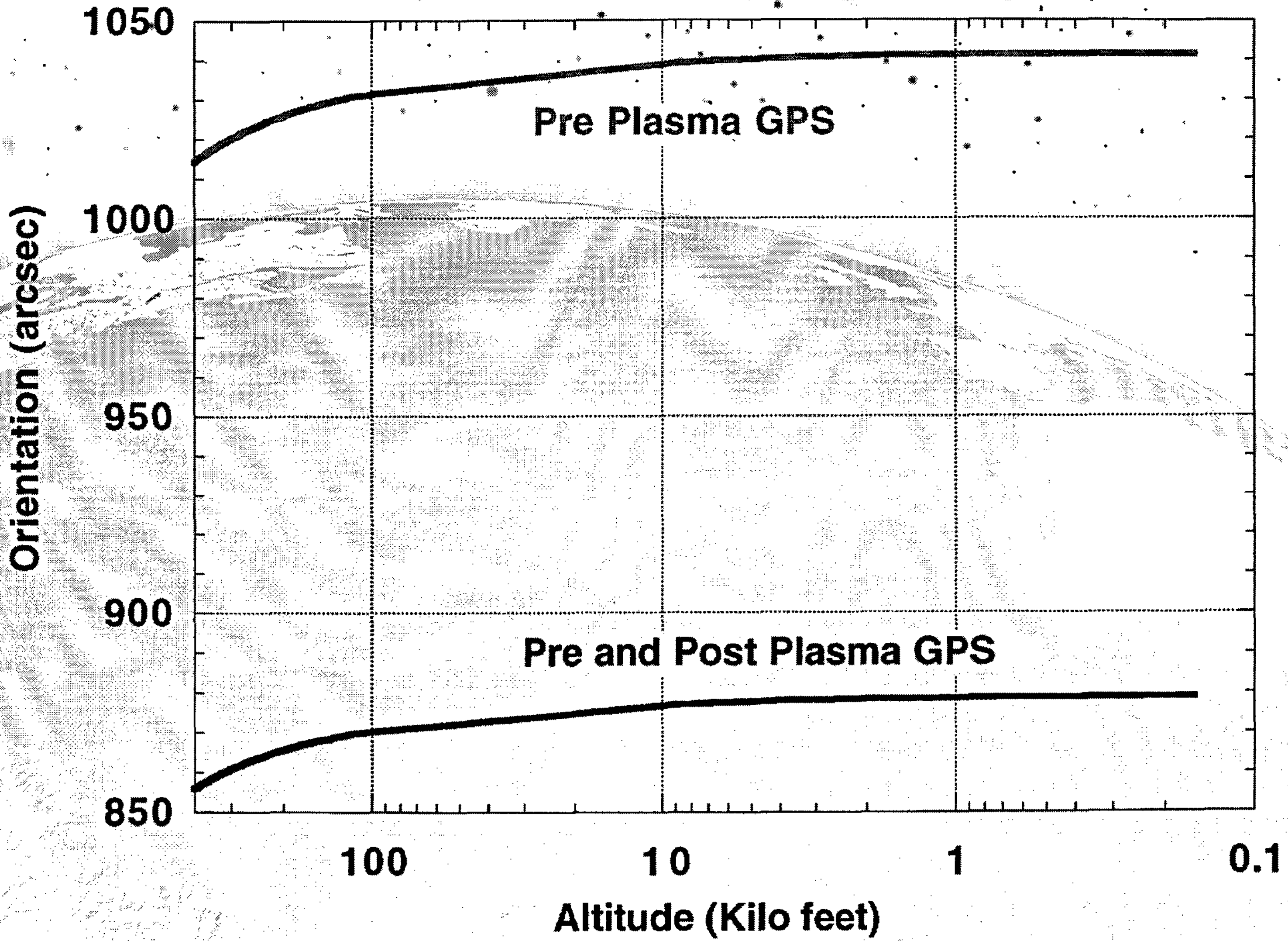

SSD-9611142-15

# Pierce Point Orientation Uncertainty
## (one-sigma, RBO frame)



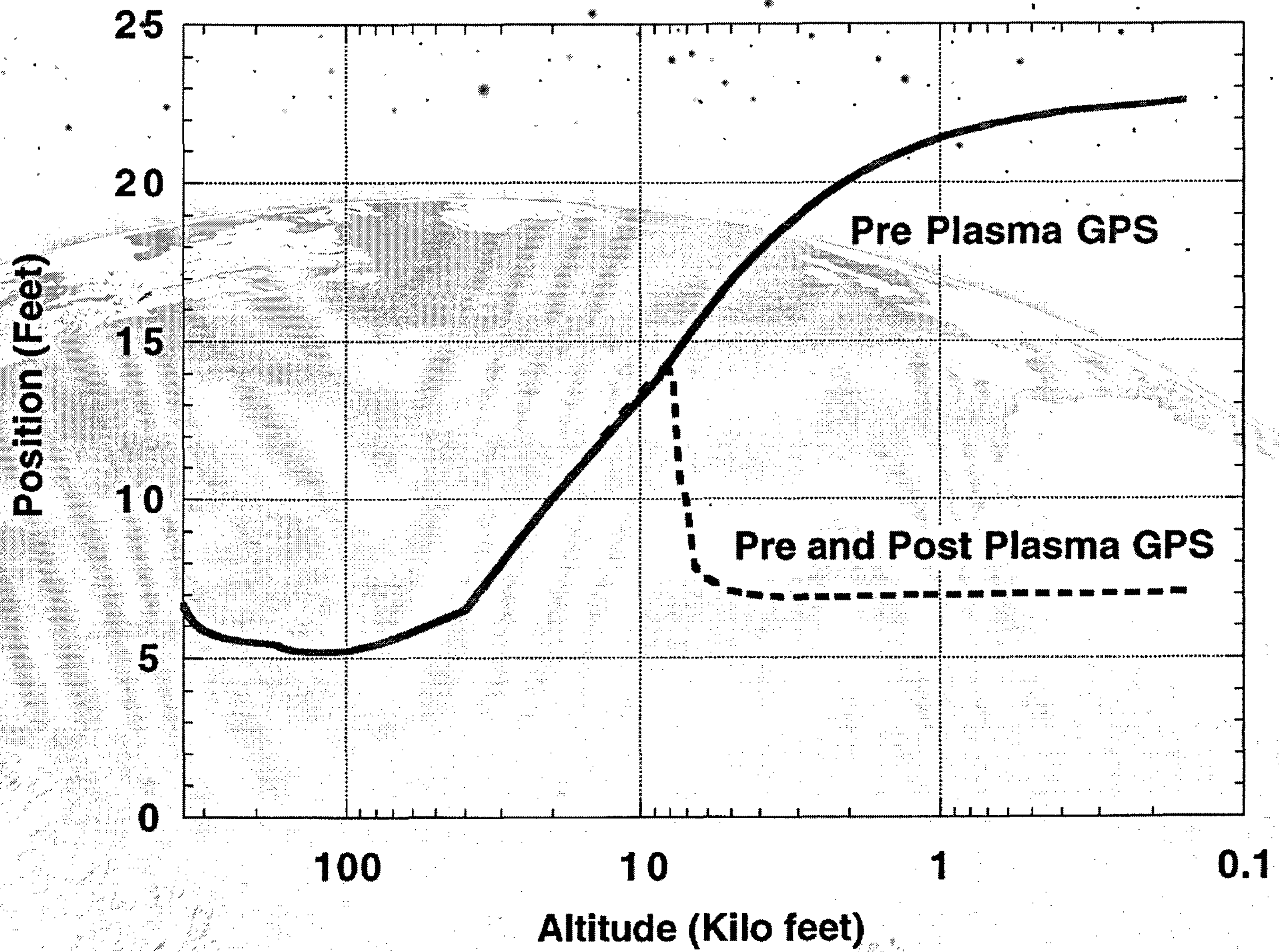

SSD-9611142-22

# INS Orientation Uncertainty for Post Processed GPS Smoother




SSD-9611142-16

# Total Position Uncertainty for GPS Filter



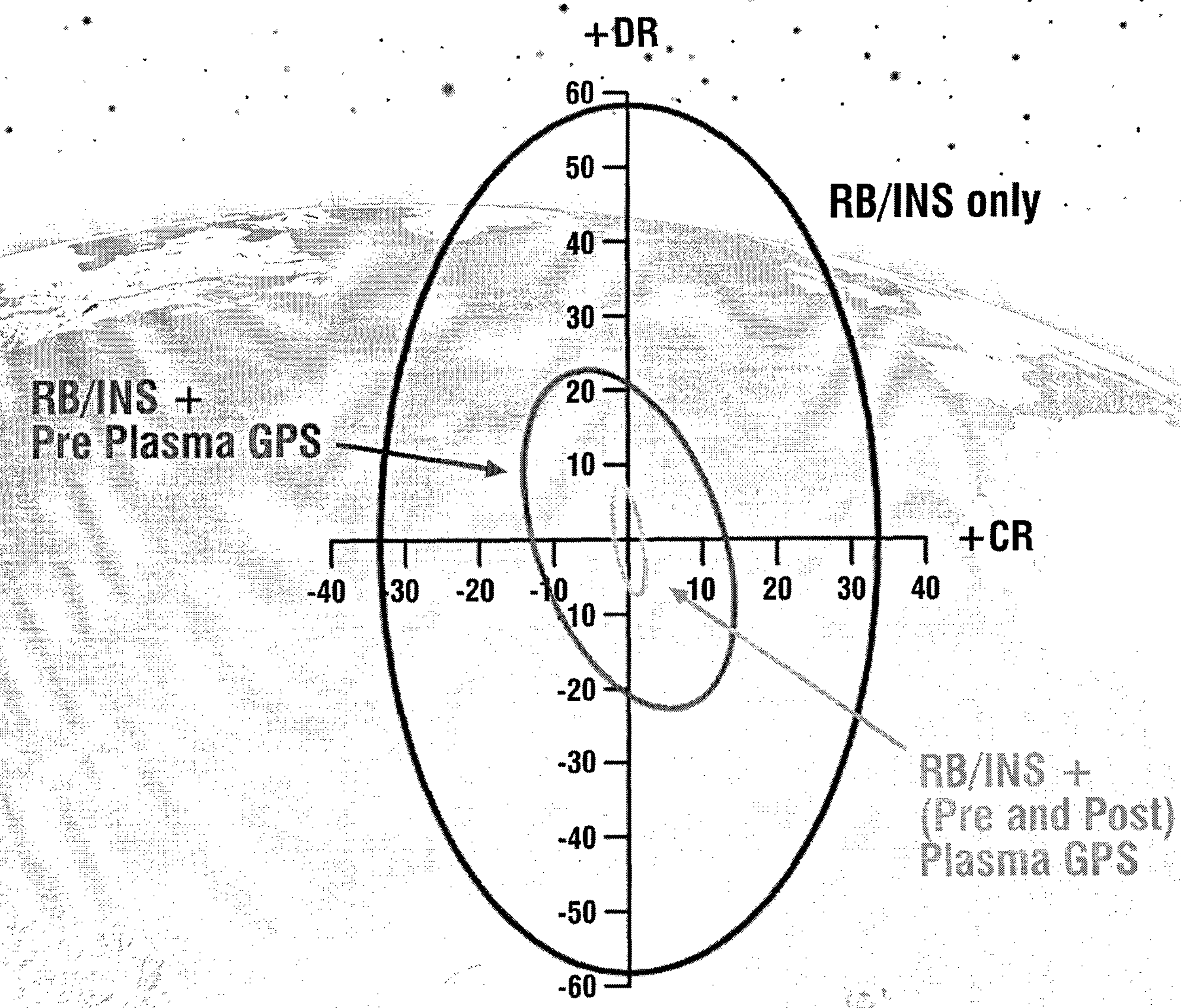

SSD-9611142-17

# BET Comparison to Impact Measurement

| | DR, FT ($1\sigma$) | CR, FT ($1\sigma$) | TOF, Sec ($1\sigma$) |
|---|---|---|---|
| RB/INS only | -138 (59) | -7 (33) | -0.0430 (0.024) |
| RB/INS + Pre Plasma GPS | -21 (23) | +3 (17) | +0.0025 (0.004) |
| RB/INS + Pre and Post Plasma GPS | +7 (7) | -10 (2) | +0.0056 (0.002) |

*($1\sigma$) = Estimation Uncertainties*

# Navigation Uncertainty at Impact




SSD-9611142-19

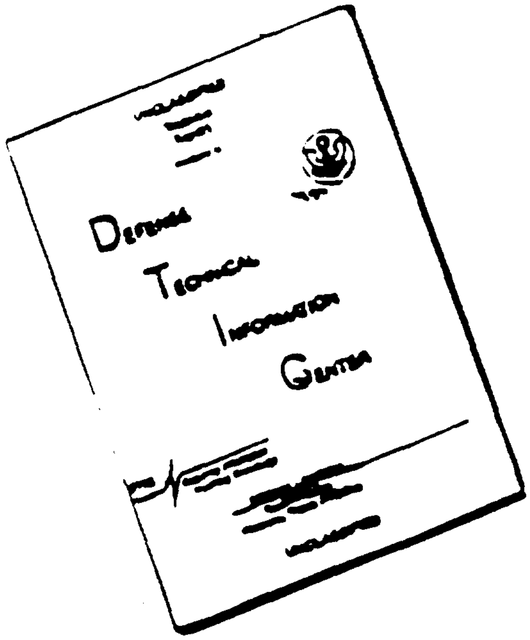
# Summary

- Successful Post-Flight Evaluation Of GPS/INS Reentry Navigation Performance
- GPS Wideband Translator And Ground Station Provided Excellent Dual Frequency Phase Data And P-Code Rage Data
  - Permitted Evaluation Of Several Scenarios Post-Flight
- GPS Data Reaquired at 8,700 Feet And Tracked To Within 60 Feet Of Surface

# Conclusions

- Use Of Pre Plasma GPS During Reentry Significantly Improved INS Trajectory And Impact Performance
- Post Plasma GPS Provided Dramatic Improvement In Predicting Impact Position And Time
- GPS/INS Test Can Aid In Development Of Integrated GPS/INS Navigator
- Provides Performance Prediction For Integrated System

# DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.